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LASER GUIDE STARS: BRIDGE OF GROUND-BASED LASERS ENTERING SPACE

by

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LASER GUIDE STARS: BRIDGE OF GROUND-BASED LASERS ENTERING SPACE

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Abstract

The principle and importance of adaptive imaging of laser guide stars in astronomy and laser astronomy are presented in the article, which also discusses laser parameters required by laser guide stars.

Key words: ground-based telescope, laser guide stars, adaptive imaging, laser astronomy.

In 1962 at the Lincoln Laboratory, the Massachusetts Institute of Technology, while emitting 50 J pulses toward the Moon at a wavelength of 694.3 nm wavelength with a 15 cm ruby laser through a Cassegrain telescope with a 30 cm alignment device, a light spot area with a diameter of 3.2 km was formed on the Moon near the Alba Douglas Mare. Coupled with a 1.22-m diameter reflective telescope, the receiver-photoelectric gain tube captured 12 echo photons. Thus, laser astronomy came into being. For the first time, mankind succeeded in returning a light beam from a celestial body^[1].

In 1964, for the first time a laser beam was reflected from an artificial earth satellite, Explorer 22, launched by the National Aeronautics and Space Administration (NASA) of the United States. Since then within a quarter of a century, researchers began to use laser devices to search for satellites at various heights that are determined by computation. The most important of these satellites are the United States geodynamics satellite and a French satellite at mean heights of 5850 and 950 km. These satellites carry fused silicon corner reflectors.

In 1969, a corner reflector was installed on the moon by the Apollo 11 crew. Since then, activities in laser astronomy have burgeoned.

In the late seventies, the geodynamics satellite and two types of altimetry satellites, the GEOS-3 and the SEASAT, marked the beginning of the satellite laser ranging project.

Satellite laser tracking (SLT) and lunar laser ranging (LLR) provide laser data for research in astronomy, relativity, geodesy, geophysics and strategic defense. These achievements include information such as the distance between Earth and Moon, gravitational field, time duration of a day, tectonic plate movements in geostructure, crustal deformations, satellite altimetry and orbital determination.

Laser ranging precision of the Moon is determined by the diameter of the laser emitting system, laser pulse width and energy. Moon researchers tend to use large astronomical telescopes as the receiver; high-energy pulsed lasers are used in lunar laser ranging.

When the energy of a laser beam emitted from a satellite laser tracking station is 1 to 3 J, the maximum range of satellite tracking range also increases from 1500 to 6000 km. Completed in 1983, the satellite laser ranging station at the Royal Greenwich Observatory (RGO) is a typical second-generation station. The output energy is 0.03 joule. As received by the ground station, the effective photoelectron number N^p is 2. The station still has a range of more than 6000 km.

Most of this progress is related to reductions in the overall divergence of the output light beam. The light beam divergence angle varies from 873 microrad in earlier periods to 100 microrad at the RGO. Further reductions to values between 50

and 60 microrad are possible. Laser ranging pulses with earlier satellites varied from 25 to 30 ns to values between 3 and 5 ns. Recently, ranging pulses reached values of 100 to 150 ps. At the mobile NASA TLRS station, pulse trains of 25 ps with bursts of 10 ps are employed; thus, it is convenient to generate recognizable photon trains at the receiver.

At present, LLR is accomplished at receivers with diameter of 75 to 80 cm. In certain situations, these stations can also accomplish satellite ranging. In 1969, the ranging error of the Earth to Moon distance was under 40 cm; at present, the average lowest mean error in laser ranging is 3 mm, while the error of Japanese researchers is 1 mm. At the Integrated Communications Research Institute of the Japanese Postal Ministry, they attained the world's highest precision in laser ranging by using artificial satellites. By employing a large 1.5-m diameter optical telescope, laser beams were emitted toward two Soviet synchronous satellites in a 20,000 kilometer high orbit, the repetition frequency is 40 Hz, and the pulse width is 100PS.

Whether or not a ground-based high energy laser beam can pass through the atmosphere to enter outer space is controlled by three factors: atmospheric turbulent flow, thermal blooming and stimulated Raman scattering (SRS). Turbulent flow in the atmosphere breaks a light beam into many small fragments, thereby degrading the light beam. At a light beam cross section with λ as the wavelength transmitted through a medium in turbulent flow, the interference distance with phase $\phi(\vec{r})$ is called the atmosphere interference length r_0 , which can be determined experimentally from the structural parameter C_n^2 of the refractive index. The parameter is a measurement property in the atmosphere. For a laser wavelength of 1 micrometer, $r_0 = 10 - 20$ cm. With time and height in a day, C_n^2 may have variations in excess of two to three magnitudes. The random

variation within a short time period (seconds to minutes) may approach a full magnitude^[2].

For a laser at a wavelength of 1 micrometer, the laser threshold value power density of SRS is between 1 and 2 MW/cm²; therefore, laser beam degeneration can be avoided by beam expansion and reduction of the output power for the laser.

Another parameter is the distortion number of thermal blooming, which causes light beam expansion due to heating at the passage through the atmosphere because of the absorption of laser energy; at the same time, variation in the refractive index gradient in air occurs. Factors affecting the thermal blooming include atmospheric absorption and the intensity of the high-energy laser beam at the layer.

The last parameter is the angle of equal thermal blooming; the angle determines the structural parameters of height and refractive index. The angle includes the relationship of the correlation angles of a phase and amplitude disturbance between two single atmospheric passages. For a laser with 1 micrometer wavelength, the angle of equal thermal blooming is approximately 20 microrad^[3] when transmitted to the same space target.

Sampling of a signal light mark and a wavefront sensor are used to pinpoint an atmospheric distortion. The introduced signal mark wavefront is broken into numerous sub-apertures, every part of which is singly focused by many small lens arrays onto a two-dimensional CCD quadrant detector array. This is the Hartman-type wavefront sensor. Thus, the mass center position of each sub-image and wavefront inclination are measured in obtaining the wavefront reconstruction signal and involves carrying out on-site resonance by using a distortion lens. Thus, a high-energy laser beam conjugated with the signal mark light beam field can be emitted^[4].

The signal mark light source is the carrier of the wavefront distortion signal. The light source is a street lamp, also referred to as a searchlight lamp or a navigation mark light lamp, thus pointing out the direction of wavefront reconstruction of field conjugation for the principal laser. Generally, the signal light source is placed on a space platform or in a relay satellite in Earth synchronous orbit. Alternatively, a retro-corner reflector can substitute for the signal mark light source. Due to considerations of the emitting advance angle and signal processing time for adaptive optical equipment, the corner reflector should be placed in front of the satellite. Thus, two equilibrium frameworks (tens of meters long, capable of stretching or contraction) with a gravity gradient can be placed to the front and to the rear of the satellite. In addition, a magnetic shock absorber is installed^[5].

In addition, since turbulent flow in the atmosphere severely constrains the resolving power of a ground-based astronomical telescope, to achieve adaptive imaging under conditions of good visibility, generally the resolving power at visible wavelengths is limited to 1 angular second for the best astronomical observatory. The angular resolving power of a ground-based telescope is $1.22 \lambda / r_0$; λ is the wavelength while r_0 is the length of the visible element in turbulent flow. At the best astronomical observatory, under conditions of good visibility $r_0 = 10 - 20$ cm, at very few optimal sites, such as Mauna Kea, occasionally r_0 can exceed 40 cm. If the telescope diameter is smaller than r_0 , the diffraction-restricted image will be focussed on a quadrant plane. However, the wavefront inclination caused by turbulent flow will cause image flicker, thus becoming obscure because of long-term light exposure. In the past 15 years, piezoelectric distortion lenses were used to compensate for turbulent flow in adaptive optical systems. All these systems require a bright reference source close to the observed target; moreover, only the brightest stars can be observed.

However, very few of the celestial body targets of interest are bright enough, or very few such targets have suitable guide stars positioned near the celestial body target to be observed (within the same angle of equal thermal blooming). Therefore, researchers discovered that adaptive imaging systems have very limited applications in astronomy^[6].

As proposed by scientists in 1985, a laser guide star (Fig. 1) was to be generated in a sodium layer in the mesoatmospheric layer with backward resonant scattering of the laser. Thus, a brand new potential prospect^[7] was inaugurated in laser astronomy.

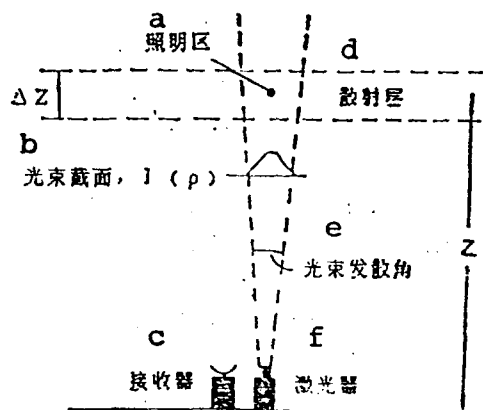


Fig. 1. Geometric relationship among laser device, receiver and scattering layer
KEY: a - illumination zone b - cross section of light beam c - receiver
d - scattering layer e - divergence angle of light beam f - laser device

As discovered by researchers, resonant scattering by sodium atoms is a relatively good approach because the cross-sectional area in backward resonant scattering by sodium is relatively large (approximately 10^{-12} cm^2). When a laser is modulated to the D_2 line of 589.0 nm, a fairly high power level can be obtained. Since the late sixties, the chemistry and dynamics of

the sodium layer were extensively studied with optical radar technology. Generally, ablation of meteorites is held to be the primary source of all alkali metals (including Na, K and Li) in the mesoatmospheric layer. One portion of the alkali originates in diffusion from oceans (this fact can account for the seasonal variations). Generally, the sodium layer is within the height range of 80 and 110 km with its peak value at 93 km. The density value there is between 10^3 and 10^4 cm^{-3} . In the mid-latitudes of the northern hemisphere, sodium column abundance ranges from the minimum summer value of $-2 \times 10^9 \text{ cm}^{-2}$ to the maximum winter value of -10^{10} cm^{-2} . Sodium abundance variations, seasonally and geographically, are related to temperature variations at the top of the mesoatmospheric layer. Sodium abundance is an important parameter for adaptive imaging because the brightness of guide stars generated in this layer is proportional to the sodium column abundance[8]. For the most effective result, the angular radius of laser guide stars should be smaller than $1.22\lambda/r_0$. The expected signal level in each sub-image can be computed from laser radar equation:

$$N \approx \eta T_A^2 \frac{r_0^2 \lambda E \sigma_{eff} C_s}{16 Z_s^2 h c (1 + \tau_n / \tau_s)} \quad (1)$$

In the equation, eta is the efficiency (approximately 0.075) of telescope and detector; T_A is the single-pass transmissibility in the atmosphere; λ is the wavelength of light ($0.589 \times 10^{-6} \text{ m}$); E is laser energy (J) in each pulse; h is Planck's constant ($6.63 \times 10^{-34} \text{ JS}$); c is the speed of light ($3 \times 10^8 \text{ ms}^{-1}$); C_s is the abundance of the sodium column (m^{-2}); τ_n is the natural life ($1.61 \times 10^{-8} \text{ S}$) of the D_2 stimulated state of sodium.

$$\tau_s \approx \frac{0.74 \pi Z_s^2 \lambda h c \tau_L}{T_A \sigma_{eff} r_0^2 E} \quad (2)$$

τ_L is the laser pulse width (S); τ_s is the saturation time; in other words, this is the characteristic time with the appearance of stimulated emission. When τ_s is much smaller than the natural life of the stimulated state, the expected

photon count derived from Eq. (1) is saturated and does not increase with pulse energy. However, for system property optimization both E and τ_p can be selected. If we let $\tau_p = (\alpha)\tau_n$ and then solve for Eqs. (1) and (2), we can obtain pulse energy E and pulse width τ_p :

$$E = \left(1 + \frac{1}{\alpha}\right) \frac{16Z_s^4 hCN}{\eta T_A^4 \lambda \sigma_{eff} C_s r_o^2} \quad (3)$$

$$\tau_p = (1 + \alpha) \frac{21.5 t_n N}{\pi \eta T_A \lambda^2 C_s} \quad (4)$$

Eqs. (3) and (4) allow us to compute the pulse energy and pulse width generated in the sodium layer as required by laser guide stars. The brightness of laser guide stars is sufficient to operate an adaptive telescope with diameter D within the diffraction limit in the atmosphere expressed in r_o .

From Eq. (1), we know that photon count is approximately 115. This photon count value should be received within the interference time (generally, it is 10 ms) of turbulent flow. To find the statistical mean of the pulse signal for better measurement precision, a certain repetition frequency (approximately 100 Hz) should exist. To attain the required photon count, the laser parameters should be selected. The three parameters should be the following: pulse width approximately 100 microseconds, pulse energy approximately 1 J, width of spectral line approximately 600 MHz, and laser wavelength $\lambda = 589.0$ nm. When the sodium layer is irradiated with an aligned high-power laser, the atomic state of the sodium layer is significantly altered because the laser power density is sufficiently high. Thus, the particle count density will have a saturation effect, which may lower the brightness of the guide star to the greatest extent. The particle count of this saturation altered state leads to nonlinear absorption of laser energy; then, the backward resonant scattering of sodium is lowered. Besides, the larger the pulse width, the smaller the

saturation effect. Thus, this laser is the more difficult to generate. To achieve night-long operation, the single pulse energy should be about 1 J. To make possible laser guide stars in all adaptive imaging systems, the light beam divergence angle (mrad) should be lowered to 5 microrad. The effective backward scattering cross section σ_{eff} is determined by the laser spectral line width and wavelength; moreover, rational selection of spectral line width can minimize the laser power requirements.

Adaptive imaging experiments in astronomy with laser guide stars were conducted in January 1987, at the Mauna Kea Astronomical Observatory in the United States, definitely confirming that this is a feasible concept of generating guide star with a laser in a sodium layer. The experiments proved that the estimated echo flux is correct. Moreover, an artificial guide star of sufficient brightness can be generated. Although much work lies ahead before large-diameter ground-based telescopes can be operated, yet even these equipment will only provide a wavefront error signal in adaptive imaging for a 1-m diameter telescope. Since the height of the sodium layer is limited and the angle of equal thermal blooming is determined by the properties of atmosphere turbulent flow, the key technique is to solve, as early as possible, the problems of generating a suitable long pulse laser with the above-mentioned parameters.

At aeronautics companies in the United States, high-power ($P_{max} = 30 \text{ kW}$, $\bar{P} = 300 \text{ W}$) capable of modulated dye lasers with long pulses (approximately 100 microseconds) were under development, long light beam quality (approximately 4 times the diffraction limit) and ultrasonic scanning light beam. As pointed out in a 1990 grant application report made by the department of astronomy and astrophysics, at the University of Chicago in the United States, two substitute laser devices based on off-the-shelf components have been studied: one is a Cu-vapor pump laser; the other is a CW Ar-ion laser as the

pumping source. Both these laser devices can generate laser beams with parameters that are close to the above-mentioned values.

Na is the most abundant alkali metal in the atmosphere and has been used as the tracer substance for temperature, diffusion coefficient of turbulent flow, and fluctuations. In the near future, the author (and his colleagues) believe that it is possible to use Na to measure simultaneously temperature and wind in the atmosphere between heights of 80 and 100 km. Therefore, once such lasers are developed, this will open up extensive application prospects in laser astronomy, adaptive optics, atmospheric remote sensing and ground-based lasers.

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